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Building confidence in CCS through on-line deliberation

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Abstract

There are a variety of stakeholders involved with CCS, including the general public who may not have relevant scientific knowledge. Although CCS is an issue for everyone, only a few people have, or have access to knowledge that is required as a basis of rationally motivated consensus. In order to resolve the situation, a mechanism that allows efficient dissemination of knowledge and expedites discussion among the stakeholders is required. The objective of this study is to develop a prototype of such a mechanism making use of information technologies and test its practicality.

The key strategy of the current study is to utilize information technology as a vehicle for disseminating knowledge of CCS and for expediting deliberation among interested individuals. More specifically, an "Internet forum" titled CO2-CoBWeb that is designated for issues concerning CCS has been formed by using JAVA-based collaborative software. CO2-CoBWeb offers a range of functionalities including, online consultation, online deliberative polling, online argumentation and online facilitation. In February and March 2008, a community consisting of some thirty members consisting of experts and interested non-experts was formed and two series of dry runs were carried out. The results revealed that the "On-line deliberation" in an Internet forum can be useful in enhancing the interactions among the members that is an essential part of confidence building in the following perspectives;

- Online consultation helps non-experts to acquire knowledge and experts to know what non-experts wish to know,
- Online argumentation among the experts on topics selected by non-experts highlights key issues in a transparent manner and offers opportunity for the members to evaluate their confidence based on the evidence referred to by the experts.
- Online facilitation supported collaboration between experts and non-experts to identify set of requirements for building confidence of the "community".

Confidence building; Decision support; Community-ware; Geological storage

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1. Introduction

Information that has been acquired through numerous existing studies and projects serves as an inventory of arguments and evidence that could be used as building blocks when we construct multiple lines of reasoning to support the long-term effectiveness of CCS. However, the process of confidence building may not be expedited merely by providing these alone.

Information and knowledge are often used in an interchangeable manner, but some important distinctions exist. Information is data endowed with meaning. In other words, information is interpreted data. On the other hand, knowledge, as in 'know how', rather than as in 'know about', is directly related to 'action'. Knowledge in this sense is the capability of a person to take an action. As proposed by Liebowitz [1], knowledge is 'the capability to act'. 'Confidence' is directly linked with some action, so that what is required is not just a collection of information concerning the features and behaviour of natural and engineered systems, but knowledge that empowers us to judge whether a CCS facility should be implemented or not. Knowledge, unlike information that can be taken away from a person who obtained it and transferred to others who need it, is very much tied up with persons who created it, so that it can only be shared among members of a 'community' who also share a variety of information, experience and practice through dynamic interactions [2]. A potentially useful class of such interactions is deliberation that appears to be an adequate medium in which the relevant arguments and evidence are integrated in an appropriate context so that they jointly contribute to forming knowledge to judge the long-term effectiveness of the confinement to be provided by CCS.

There are a variety of stakeholders concerning CCS, including the general public who may not have relevant scientific knowledge. Although CCS is an issue for everyone, only a few people have or have access to knowledge that is required as a basis of rationally motivated consensus. In order to resolve the situation, a mechanism that allows efficient dissemination of knowledge and expedites discussion among the stakeholders is required. The objective of this study is to develop a prototype to such a mechanism making use of information technologies and to test its practicality.

Information technologies have had a significant impact on society and our way of our life. It has brought about a synergetic effect: the greater the number of people connected to information networks, the greater the amount of information, knowledge, and services become available beyond spatial and temporal constraints. The key strategy of the current study is to utilize information technologies as vehicles for disseminating knowledge of CCS and for expediting deliberation among interested individuals. More specifically, an "Internet forum" titled CO2-CoBWeb that is designated for issues concerning CCS has been formed and the possibility of confidence building through on-line deliberation was explored by using this as a platform.

2. Confidence building as a knowledge creation process

In order to enhance confidence relating to actions and decisions concerning a multidisciplinary project such as CCS, developing a 'meta-community' that integrates existing academic and industrial communities and expedites dynamic knowledge interactions is of crucial importance. Furthermore, a variety of non-expert stakeholders also need to be involved in this meta-community. For this very reason, building confidence in CCS requires active participation of stakeholders from different backgrounds and possessing different value systems. Two directions in confidence building regarded as a process of creating social knowledge that empowers us to judge whether geological storage of carbon dioxide can be counted as an effective measures against global warming, are summarised below.

2.1 Knowledge management in a multi-disciplinary project

The assets of a multidisciplinary community can be classified as either explicit knowledge that can be expressed in terms of language, figures or equations and communicated among members, or tacit knowledge that they acquired through experience and unconsciously have in their brain. Nonaka and Takeuchi argue that active interaction of these two kinds of knowledge is a driving force of creative enterprises [3]. They describe a knowledge spiral model consisting of four stages: externalization, combination, internalization, and socialization. At the externalization stage, explicit knowledge is created by representing expertise as explicit concepts. At the combination stage, new explicit knowledge is created by combining existing explicit knowledge. At the internalization stage, tacit knowledge is created by using explicit knowledge to perform tasks in an interpretive fashion. Such tacit knowledge, then, diffuses into a community and new tacit knowledge is created as shared expertise at the socialization stage.

From the perspective of confidence building, a multidisciplinary research project of a CCS can be regarded as a knowledge-creating community [2] and networking of various experts relevant to CCS should be encouraged. The essence of knowledge management is how members of the community do the following [4]:

- *Generate and acquire knowledge* – this relates to how members measure and foster productivity and creativity, identify weaknesses in their competence and decide how to correct them (e.g., by hiring experts in appropriate fields, training their personnel, incorporating novel technologies, etc.).
- *Store and preserve knowledge* (often quoted as 'organizational learning' – this relates to how knowledge can be preserved within a community once it has been obtained.
- *Access and use knowledge* – this relates to how members identify relevant pieces of knowledge when facing new situations and challenges and what is needed to build a structure such that those pieces of knowledge can be efficiently retrieved when necessary.
- *Distribute and disseminate knowledge* – this is based on the assumption that knowledge is distributed across communities. Hence, different members hold different skills and capabilities. This adds a new dimension to the access and use of knowledge, requiring members to be capable of communicating with each other, expressing capabilities they may need, problems they may be interested in delegating to other members, as well as solutions to delegated problems.

2.2 Chain of trust

There is a hierarchy of issues relating to CCS that are nested in each other. A variety of stakeholders with different interest and value systems have concern in issues at a higher level, e.g., the effectiveness of CCS as a measure to prevent global warming, in which a higher degree of 'publicness' is involved. In order for them to resolve these issues, however, a number of related technical and/or scientific questions concerning, e.g., site characterisation, reservoir engineering and more specific technical/scientific issues, need to be answered. Because of the nature of these questions, most of the stakeholders do not have a direct interest. Through active participation in the knowledge creating process, their literacy may be improved to some extent, but it requires significant time and effort for every stakeholder to be capable of dealing with these issues in detail. Therefore it is necessary for them to delegate tasks of answering these questions to those who have relevant expertise. The delegation is possible only when there is 'trust' between experts and non-expert stakeholders based upon fact supporting the arguments, legitimacy and authenticity of their behaviour.

A variety of questions will be asked by a wide range of stakeholders, including those concerning the scientific basis for geological storage, monitoring and remediation, legal framework, responsibility to short term socio-economical impacts as well as potential environmental impact in the future, procedure of implementation and decision processes. This is a reflection of the fact that they have a spectrum of concern and opinion depending on their own interest and value systems. Therefore dialogue with them will provide the technical community opportunities to test their arguments from different perspectives, some of which they have never been aware. In most of the cases the questions can be answered and their concerns be settled. However, some of them prove to be difficult to answer mainly because the technical community is not aware of the problem. In these cases, it is important to accept perspectives that are totally different from those of the scientific/technical experts and to look for a best solution. In order to evaluate their relative weight without biases, perhaps it is important to form a group whose members are from a range of different backgrounds (including non-technical ones).

The dialogue with stakeholders should be regarded by the technical community as a mechanism to develop their knowledge through chains of argumentation into common knowledge of a merged 'community' that will be formed in parallel. Since this is a dialectical process of knowledge creation, members of the technical community must not pretend that they know answers to all the questions asked, or restrict scope of the dialogue to what they think important. On the contrary, they should try to understand value systems that are totally different from theirs and be prepared to accept the existence of open questions.

3. Hierarchy of arguments supporting effectiveness of geological storage

Arguments and evidence supporting long-term confinement of CO_2 by geological storage was reviewed based around a framework presented by Benson [5], namely, the notion of a 'safety and security pyramid', which engenders confidence in the carbon capture and storage (CCS) concept.

At the base of the pyramid lies the *fundamental scientific knowledge of storage and leakage mechanisms*. As Audus [6] has pointed out, the scientific and technological understanding of CO_2 capture and storage is well-advanced, so that remaining uncertainties relate to convincing the general public that storage is safe and secure, whilst demonstrating the capacity and effective containment for so-called 'saline aquifers'. Analogues serve a number of purposes linked to improving our understanding, with the most quantitative purpose being the validation of predictive modelling results. In the absence of quantitative information, analogues can be used to support risk communication with stakeholders, by identifying geological environments that are suitable for long-term CO_2 storage, and, on the other hand, by explaining why poor sites leak. Moreover, indications are that science-based information is not sufficient to satisfy public concerns, and other avenues of communication, e.g., natural and industrial analogues, are needed to support the science-based approach, particularly when safety assessment techniques are not easy to communicate.

Effective site selection and characterisation methods: In a review of the status of CCS, Audus [6] concluded that sufficient geological storage capacity is available, with oil and gas fields providing significant global storage capacity. So-called 'best practice manuals' being developed for a variety of projects and sites help point the way forward with regard to site selection and characterisation. For example, the SACS Best Practice Manual [7] recommends that it is necessary to characterise the reservoir and caprock on both local and regional scales to elucidate CO_2 migration patterns and overall storage potential. This involves a determination of structure and stratigraphy both within and external to the reservoir, together with the physical properties of both the reservoir and caprock. The SACS Best Practice Manual [7] suggests various recommendations for different aspects of characterisation, based on the experience during the SACS project, where geoscientific appraisal of the reservoir (the Utsira Sand) and its caprock was carried out at a range of scales. The whole reservoir (some 26000 km^2) was mapped and characterised using regional 2-D seismic datasets and well data. More detailed work was carried out around the injection site using a 3-D seismic dataset and more closely spaced well data.

Much information for *storage engineering* and *safe operations* can be established from the oil and gas industry [5]. As Benson [5] illustrates, industrial and natural analogues are useful for understanding and quantifying risks. For example, the oil and gas industry has a safety record comparable to many ongoing activities, and incidents such as well blowouts are rare events. The safety and security pyramid outlines and explains diligent operations, oversight and financial responsibility. Long-term storage security risks can be informed by operational performance from the oil and gas industry. This experience would suggest that the greatest risks occur during operational phase. However, more commercial-scale CCS projects are needed to build confidence.

Monitoring: Recent reviews (e.g. [8], [9], [10], [11], [12]) have demonstrated that technology is well advanced to monitor the presence of CO_2 underground and to be able to assess leakage with the relevant detection limits. A number of studies have been carried out to evaluate suitable techniques for CO_2 monitoring which show that a large range of techniques is available at a relatively low cost (US$0.10-0.30 per tonne of CO_2 – [11]). For example, Benson [11] has shown that if a storage reservoir is overlain by a saline formation beneath a secondary seal, pressure monitoring and seismic imaging can be extremely effective for detecting migration out of a storage reservoir, particularly near known faults, or abandoned wells. Schematic calculations of pressure increases show that measurable pressure changes (>0.007 bars) would occur within a year for leaking faults located within a kilometre of the injection well for a wide range of permeabilities. Similar calculations show that for leakage around a well casing, there is a high probability of detecting leakage of the order of 5000 tonnes/year at distances of up to 1 km. Where secondary seals are unavailable, atmospheric and near-surface monitoring may be a preferred approach, focusing on abandoned wells and surface expression of faults and fractures. Plane-based or satellite-based hyperspectral imaging could be used to locate areas where emissions are likely. If emissions are detected, then the precise location can be determined using flux chambers or soil gas monitoring. Seismic monitoring can be equally as effective [11]. Studies have shown that CO_2 accumulations as small as 100 tonnes could be detected at a depth of about 500 m. Under these conditions, it would be reasonable to conclude that if there were no migration of CO_2 out of the storage reservoir, this should suffice as 'proof' that there are no emissions for the reservoir [11].

Remediation methods: Any monitoring programme should be intimately linked with remediation plans, since appropriate remediation action cannot be taken without supporting monitoring data. The success of any actions taken must also be measured. As Pearce et al. [12] have discussed, one important aspect of the remediation plan is the definition of appropriate thresholds, or events, that require some remediation. Accurate, comprehensive baseline monitoring data are crucial in establishing appropriate safety levels or trigger thresholds. Thresholds can be applied to a wide variety of parameters including annular well pressure, microseismicity, soil gas CO_2 concentrations, atmospheric CO_2 concentrations, fluid geochemistry, reservoir pressure or temperature, and tracer concentration. With regard to ecosystems, target indicator organisms could also be selected. Pearce et al.[12] suggest that activities that could be implemented as a result of reaching a specific threshold or trigger event, could include increasing the frequency of current monitoring, implementing additional monitoring techniques, revising geological models and storage estimates, delay of implementation of the next stage in the project, change of operations, well work-overs, instigating remediation plans and informing the regulator(s).

Regulatory oversight (in relation to risk/safety assessment, in particular) has been discussed in detail by Stenhouse [13]. Stenhouse [13] concluded that a phased approach to storage projects is beneficial to stakeholder acceptance, but that safety/risk assessment and its results are not sufficient to install confidence in all stakeholders. To develop technical standards or a flexible protocol-based framework, it is necessary to build on existing documents, such as Best Practice Manuals, and national standards for risk analysis. Stenhouse [13] considers that monitoring needs to provide quantitative resolution capability to match requirements through confirmation of safety/risk assessment predictions and quantification of migration of CO_2 for GHG inventory purposes.

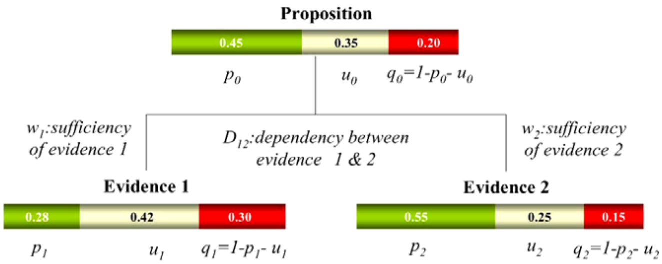
4. Evidence-based approach to assess confidence

Multiple lines of reasoning based on a variety of sources of evidence are necessary in order to develop a robust argument to support the long-term effectiveness in the presence of uncertainty and to communicate confidence among various types of stakeholders with different value systems. In a recent study, an approach based on ESL (Evidential Support Logic [14]) was employed to construct and analyse the logical structure of judgments of our confidence and the dependence on various pieces of evidence. Suppose a proposition is formed supporting long-term confinement of CO_2 by geological storage. The first task of ESL is to unfold this proposition by constructing a process model. The 'top' proposition is subdivided iteratively to form an inverted tree-like structure, with propositions at each lower level corresponding to intermediate interpretations. The subdivision is continued until the proposition becomes sufficiently specific, and evidence to judge its adequacy becomes available. After constructing the process model, confidence in the top proposition is evaluated. The degree of confidence in the support for each lowest-level proposition is estimated, usually based on expert judgement, from corresponding information (*i.e.* evidence) and propagated through the process model using the simple arithmetic given below. The degree of confidence that some evidence supports a proposition can be expressed as a subjective probability given by experts in the subject area. However, since evidence concerning a complex system is often incomplete and/or imprecise, it may be inappropriate to use the classical (point) probability theory. This theory cannot account for uncertainty in an actual evaluation of support, because if some evidence supports a proposition with probability p, the probability against the proposition is automatically $1-p$. For this reason, ESL uses Interval Probability Theory, which allows one to say "the degree of confidence that evidence supports the proposition lies between p and $p + u$". In this case, the degree of confidence that evidence does not support the proposition is between $1-p-u$ and $1-p$. Hence we have:

- A minimum degree of confidence that some evidence supports the proposition is p;
- A minimum degree of confidence that some evidence does not support the proposition is $1-p-u$;
- The uncertainty is u.

The arithmetic to propagate degrees of confidence upward through the process model is depicted in Figure 1, where the 'sufficiency' of an individual piece of evidence or lower level proposition can be regarded as the corresponding conditional probability. That is, 'sufficiency' is the probability of the higher level proposition being true provided each piece of evidence or lower level proposition is true. A parameter called 'dependency' is introduced to avoid double counting of support from any mutually dependent pieces of evidence.

The approach based on ESL is applicable to the deliberation process concerning a wide range of technical and non-technical arguments. The deliberation process consists of provision of all the relevant information and related technical articles, discussion concerning the structure of the process model for evaluating confidence in each component of the system, evaluation of the sufficiency of auxiliary propositions and evidence as well as the subjective probability of each piece of evidence supporting or disqualifying the propositions. The minimum degree of con fidence, p, is set to be the minimum value of the subjective probability provided by the experts, while the difference between the minimum and the maximum value is regarded as u whenever the opinions of the experts do not converge.



$$p_0 = w_1 p_1 + w_2 p_2 - \rho_{12} Min(w_1 p_1, w_2 p_2)$$

$$q_0 = w_1 q_1 + w_2 q_2 - \rho_{12} Min(w_1 q_1, w_2 q_2)$$

where $$\rho_{12} = \frac{(1-D_{12})(w_1 p_1 \ w_2 p_2)}{Min(w_1 p_1, w_2 p_2)} + D_{12}$$

Figure 1 Evaluation of confidence using Interval Probability Theory.

It should be noted that results of the ESL evaluation is dependent on the value system associated with members of the group and, therefore, can vary. However this is still useful in expediting the communic ation of confidence among a spectrum of stakeholders in a transparent manner.

Confidence building is an iterative process where evaluation of confidence based on the evidence available at a stage should be utilised as a useful input to planning of the next stage of the reservoir system development. For this purpose, a sensitivity analysis of ESL can be carried out to evaluate the relative importance of new evidence that could be obtained at subsequent stages. In the case of ESL, by increasing the support from each proposition at the bottom level and calculating how confidence of the top proposition can be improved, the relative contribution of each proposition to confidence enhancement can be evaluated in advance. The sensitivity of each proposition thus obtained reflects efficiency in propagation of the unit increase of confidence affected by sufficiency of all the propositions at the interim levels.

5. On-line deliberation

Taking all the factors discussed in the previous sections into account, an on -line community (more specifically an "Internet forum" titled CO2 -CoBWeb, designated for issues concerning CCS), was formed so that methodologies for expediting confidence building among a variety of stakeholders could be tested so that lessons could be learnt through this exercise. In addition, a tool to support members of the community to generate, acquire, store, preserve, access, use, distribute, and disseminate knowledge, was developed using JAVA -based collaborative software. CO2 - CoBWeb offers a range of fu nctionalities including, access to the information -base summarized in Section 3, online consultation, online deliberative polling, online assessment of confidence using ESL (see Section 4) and online facilitation.

In February and March 2008, a community c onsisting of some thirty members, experts, and interested non -experts, was formed and two series of dry runs were carried out. Based on the concept of a "knowl edge creating spiral" that was mentioned in Section 2, during the first dry run in February 2008 a series of discussions were made among experts and non -expert members to share information summarized in Section 3 and identify issues to be discussed further by the community members through online consultation and online deliberative polling. In March 2008, the second dry run was carried out in which all the members were invited to collaborate in finding answers to the following questions;

- "What arguments are required for a variety of stakeholders including non -experts to be convinced of implementing geological storage of CO_2 in a saline aquifer in Japan?",
- "Can experts and relevant organizations present required arguments with supporting evidence?".

The second dry run consists of the following four stages;

- Stage 1; Discussion among all the members to i dentify arguments that could convince the stakeholders of implementing geological storage in Japan,

- Stage 2; On-line deliberative polling on sufficiency of each argument to support the decision, i.e., conditional subjective probability of supporting implem entation of geological storage if each argument is made successfully,
- Stage 3; Collaboration of experts to develop arguments and collate supporting evidence into the information - base followed by their presentation to other members and questions/discussions,
- Stage 4; On-line deliberative polling to assess the degree of confidence in each piece of available evidence to support the relevant arguments.

Table 1 summarises the arguments identified in Stage 1 and a "wish list" for supporting evidence.

Table1 Arguments for implementing geological storage of CO2 in a saline aquifer in Japan and supporting evidence identified during the second dry run of CO2-CobWeb

Arguments identified by members of CO2-CobWeb	Supporting evidence
Arg. 1; CCS is the only practical option at hand against global warming.	Evd. 1-1; Results of analyses suggesting emergency of measures against global warming and time required for implementing methods other than CCS
Arg. 2; Cost for CCS is at an acceptable level.	Evd. 2-1; Estimation of cost for CCS
	Evd. 2-2; Incentives such as carbon tax
Arg. 3; There exists sufficient scientific understanding of transport of the super-critical CO_2 and its phase change at depth.	Evd. 3-1; Scientific basis for all the relevant features and processes
Arg. 4; There exists sufficient scientific understanding of interactions between CO_2 saturated ground water and concrete sealing.	Evd. 4-1; Experiments and modelling on reactions of cement with CO_2 saturated groundwater
	Evd. 4-2; Data from cement bond log after completion of wells
	Evd. 4-3; Experiments and modelling demonstrating formation of protective layers of secondary minerals on cement surfaces
Arg. 5; There exist well-defined criteria and guidelines for site selection.	Evd. 5-1; Existence of in ternational guidelines for selecting favourable sites
	Evd. 5-2; Existence of Japan-specific criteria for choosing candidates sites
Arg. 6; Environmental impact in case of major leaking of CO2 from the reservoir due to events such as seismicity is not ex cessively large.	Evd. 6-1; Analysis of the impact of major leaking from a reservoir
Arg. 7; Any significant leakage of CO_2 from the reservoir can be detected by existing monitoring techniques.	Evd. 7-1; Existence of valid monitoring techniques
	Evd. 7-2; Detection of CO_2 leakage by 3D seismic monitoring at Sleipner
	Evd. 7-3; Possibility of detecting CO_2 leakage by water sampling at Nagaoka
Arg. 8; There are organizations that are responsible for leakage of CO_2 during operation and post-operational monitoring period.	Evd. 8-1; Legal framework defining responsibility during operation and post-operational monitoring period
Arg. 9; There are organizations that are responsible for leakage of CO_2 after operation of a reservoir.	Evd. 9-1; Experts' opinion on who should be responsible in distant future
	Evd. 9-2; Legal framework stating that responsibility in future belongs to the goverment

An ESL analysis on the set of arguments based on "sufficiency" of each argument and confidence in each supporting evidence defined by online deliberative polling at Stage 2 and 4 respectively was carried out and the result is shown in Figure 2 (left), which implies that confidence in implementing geological storage (green bar in the top box) is greater than that against (red bar) but significant uncertainty (white) remains. A sensitivity analysis (Figure 2 (right)) revealed that new evidence relating to socio-political arguments could have a large positive (green bars), i.e., increase in overall confidence when it is supporting the argument, and negative impacts (red bars), while some new scientific information can affect the results as well.

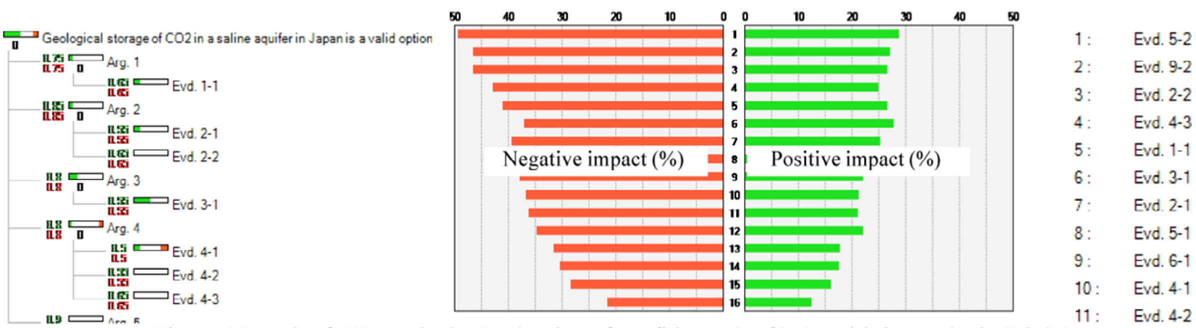


Figure 2 Result of ESL analysis; Evaluation of confidence (Left), Sensitivity analysis (Right)

6. Conclusion

As a mechanism that allows efficient dissemination of knowledge and expedites discussion among the stakeholders, a prototype of community-ware for disseminating knowledge of CCS and for expediting deliberation among interested individuals was developed by using a JAVA-based collaborative software. A community of some thirty members, consisting of experts and interested non-experts was formed and two series of dry run were carried out. The results revealed that the "On-line deliberation" in an Internet forum can be useful in enhancing the interactions among the members that is an essential part of confidence building in the following perspectives;

- Online consultation helps non-experts to acquire knowledge and experts to know what non-experts wish to know,
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